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ONE WAY IMAGING AND AMPLIFICATION THROUGH AN ABERRATOR

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This report presents the results of an experiment combining one-way image reconstruction using four-wave mixing in carbon disulfide with optical parametric amplification in lithium iodate. A mode-locked Nd:YAG laser was used as the light source, and a resolution target provided the image. The distortions caused by a severe static aberrator were corrected, but only when the four-wave mixing process was confined to a short interaction length and strict alignment conditions were satisfied. The optical parametric amplifier was then used to amplify the distortion-corrected image.

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1.0 INTRODUCTION

The goal of this project was to demonstrate that two nonlinear optical techniques could be combined in a system capable of transmitting an image through an aberrating medium, recovering the original image, and then amplifying and processing the image. Aberration correction was accomplished using a polarization-splitting one-way imaging scheme, while the amplification and processing was performed by a downconverting optical parametric amplifier (OPA).

Several schemes have been demonstrated which can receive a coherent, distorted signal beam, along with a reference beam, and reproduce the undistorted signal using a four-wave mixer (FWM) (Refs. 1-3). In this experiment, a linearly polarized image beam and an orthogonally polarized reference beam were passed through the same portion of the aberrator, as in Refs. 1 and 3. The orthogonally polarized components were separated after the aberrator and used as the probe and the forward pump in a four-wave mixing geometry. The phase aberration which was common to both beams was subtracted and the original image was recovered on the "phase-conjugate" beam.*

A down-converting OPA can amplify certain spatial frequencies of a monochromatic image (Refs. 4 and 5). The energy required for the amplification comes from a pump beam which is at a higher frequency than the image beam. Using a type I angle-tuned crystal, such as lithium iodate, the OPA is a low-pass spatial frequency filter when it is tuned to the correct phase-matching angle for the wavelengths involved. When the crystal is

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* The output beam from the FWM is not a true phase-conjugate of the probe in this experiment, since the two pump beams are not phase-conjugates of each other. The phase of this "phase-conjugate" beam is actually equal to the phase of the counterpropagating pump (assumed to be uniform) plus that of the forward pump, minus the phase of the probe. Thus, the term "phase-conjugate" is used loosely in this paper.

tuned to one side of this angle, a phase-mismatch is produced which shifts the peak of the OPA's transfer function to nonzero spatial frequencies. The pass-band also narrows with increasing phase-mismatch. In this way, portions of the input image spectrum can be selectively amplified by merely rotating the OPA crystal through a small angle.

2.0 ONE-WAY IMAGING

2.1 EXPERIMENT

The experimental layout for the one-way imaging portion of the experiment is shown in Fig. 1. A mode-locked Nd:YAG laser with a second harmonic generator was used in this experiment. The laser produced 100 ps pulses at a 10 Hz repetition rate. The single pulse energy was about 4 mJ at the 1064 nm wavelength and 3 mJ at 532 nm. The 532 nm beam was first split off from the 1064 nm beam by a harmonic beamsplitter and used for the OPA pump, which will be described in Section 3.0. Next, part of the linearly polarized 1064 nm beam was split off to be the counterpropagating pump of the FWM. The rest was converted to elliptical polarization by a quarter-wave plate and then split into orthogonal linearly polarized components by a polarizing beam splitter (PBS). The reflected component was passed through a resolution target. The beams were then recombined by another PBS and passed through the aberrator. The aberrator was an acid-etched glass plate ≈ 2 mm thick. It was essential that the two beams were recombined so they both passed though an identical section of the aberrator.

The orthogonally polarized components of the beam were then separated by a PBS and overlapped within the FWM, which was a glass vial filled with carbon disulfide (CS_2). The reflected component, containing the aberrated image, served as the probe, while the other component, containing the aberrator reference information, served as the forward pump of the FWM. The aberrator was imaged into the FWM using three 50-cm focal length lenses. These were placed to provide 1:1 magnification and to preserve the collimation of the beams. A half-wave plate was inserted into the probe

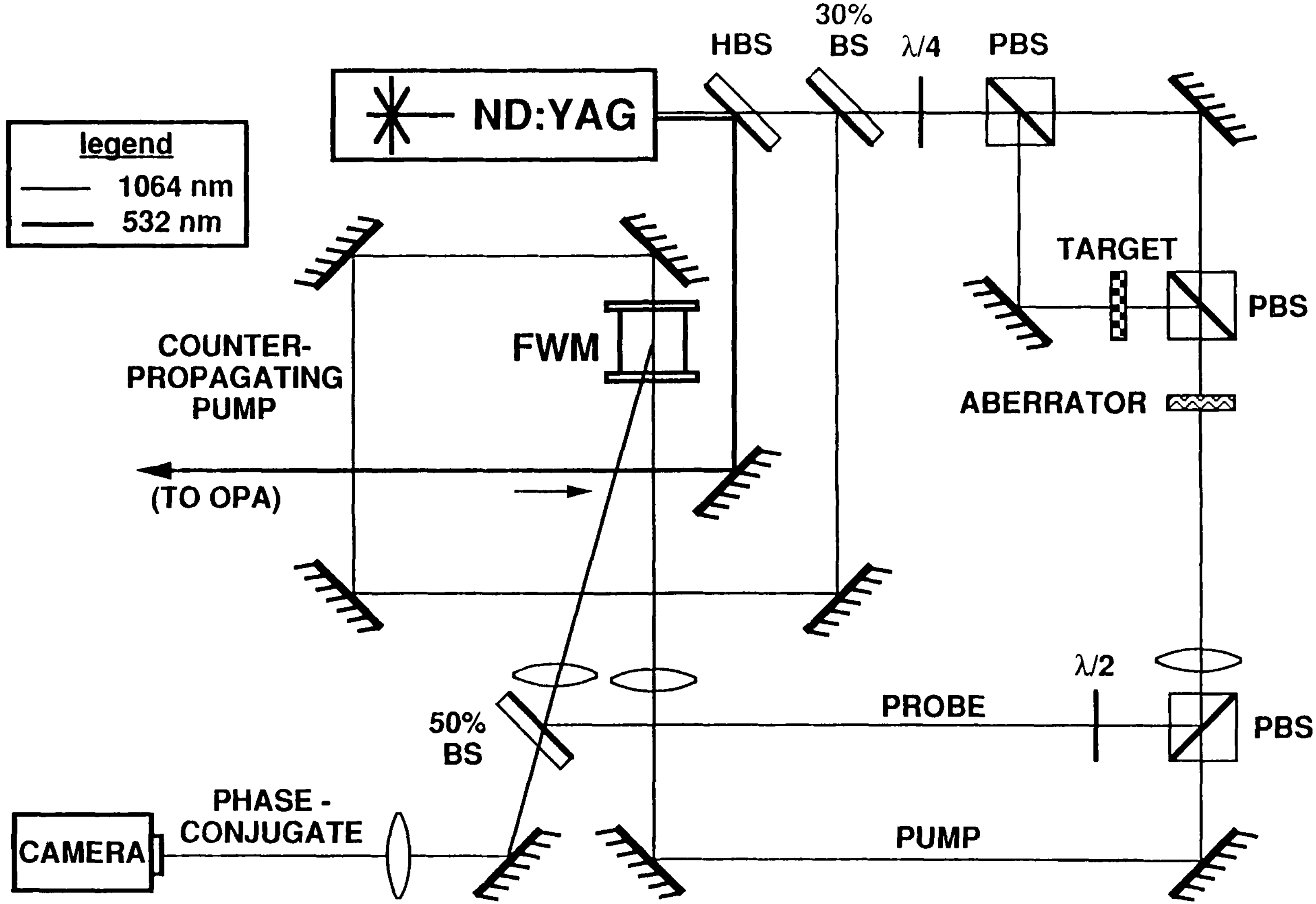

Figure 1. One-Way Imaging Layout. BS: beamsplitter, HBS: harmonic beamsplitter, PBS:polarizing beamsplitter, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate. Small arrow indicates position of retroreflecting ordinary mirror.

beam so that all three inputs to the FWM would be of the same polarization. This was done to increase the reflectivity of the phase-conjugate.

The four-wave interaction produced a phase-conjugate which was separated from the probe by a 50 percent beamsplitter. The lenses imaging the aberrator onto the FWM also imaged the target to a distance in front of the FWM equal to target-aberrator separation. Upon conjugation, this intermediate image of the target was re-created on the phase-conjugate beam. Fifty-centimeter focal length lenses relayed this intermediate image plane onto a charge-injection device (CID) video camera for observation. To observe the uncorrected image for comparison, an ordinary mirror was placed at the intermediate image plane to retroreflect the probe. With this procedure, no other optics had to be moved, and the optical paths of the corrected and uncorrected images were the same, except for the FWM.

2.2 RESULTS

Other types of aberrators were tried before deciding on the acid-etched glass. Originally a hot-air aberrator was used; however, the characteristic size of the turbulence produced was on the order of the beam diameter ($\approx$ 1 mm) and thus the aberration was slight. The acid-etched glass, however, had the fine-grained quality needed to distort the image noticeably. In the continuous wave (CW) experiments of Ref. 3, the hot-air aberrator provided significant distortion because the CW laser allowed observation of an average of the turbulent hot-air flow. Since the pulse duration in this experiment was very short, the hot-air flow was instantaneously sampled by the laser pulse, and this averaging was lost. This property can be an advantage. The very short pulse, when combined with a fast nonlinear material, simply treats the dynamic aberrators as static.

Two factors were critical in the alignment of the apparatus. First, proper temporal overlap at the FWM required that the total optical path lengths of the two pumps and the probe, from the laser to the FWM, be equal to within 1 cm. Second, precise spatial overlap of the forward pump and the

probe beams was required at the FWM. However, exact spatial overlap (except for a small tilt) can occur at only one plane within the FWM, because of the crossing angle between the probe and the pumps. Other planes within the cell are "mis-indexed," i. e., the aberrations on the pump and probe are not exactly overlapped there. This spatial offset means that the phase-subtraction at the mis-indexed transverse planes will not fully correct for the effects of the aberrator.

Initially, a 10-mm-long cell of CS_2 was tried. Although the phase-conjugate was easily observed, there was no evidence of aberration correction. This was caused by the large proportion of mis-indexed planes contributing to the total phase-conjugate return. With a 5-mm cell, the aberration correction was still nonexistent, but with a 2-mm cell, aberration correction was finally observed. The performance improved further using a 1-mm cell. Although there was a reduction in the phase-conjugate intensity with the decreasing cell lengths, the extra intensity had come from the mis-indexed regions in the CS_2, and was not useful. Figure 2 shows the best results obtained with the 1-mm cell. The target elements shown in the phase-conjugate photograph have spatial frequencies of about 5 lines per millimeter.

Even with the 1-mm cell, the spatial overlap at the cell remained crucial. By observing the image quality of the phase-conjugate, it was possible to adjust the probe for best overlap with the forward pump, and hence maximum aberration correction. The resolution required for this adjustment nearly exceeded the capabilities of the standard gimbal mount that was used. The slightest misalignment resulted in markedly decreased aberration correction.

The effect of moving the aberrator so that it was not imaged exactly in the FWM was also investigated. The aberrator could be moved about 1 cm in each longitudinal direction, with the system still maintaining good aberration correction. The relationship between the ability to correct for thin, non-imaged aberrators and the ability to correct for thick,

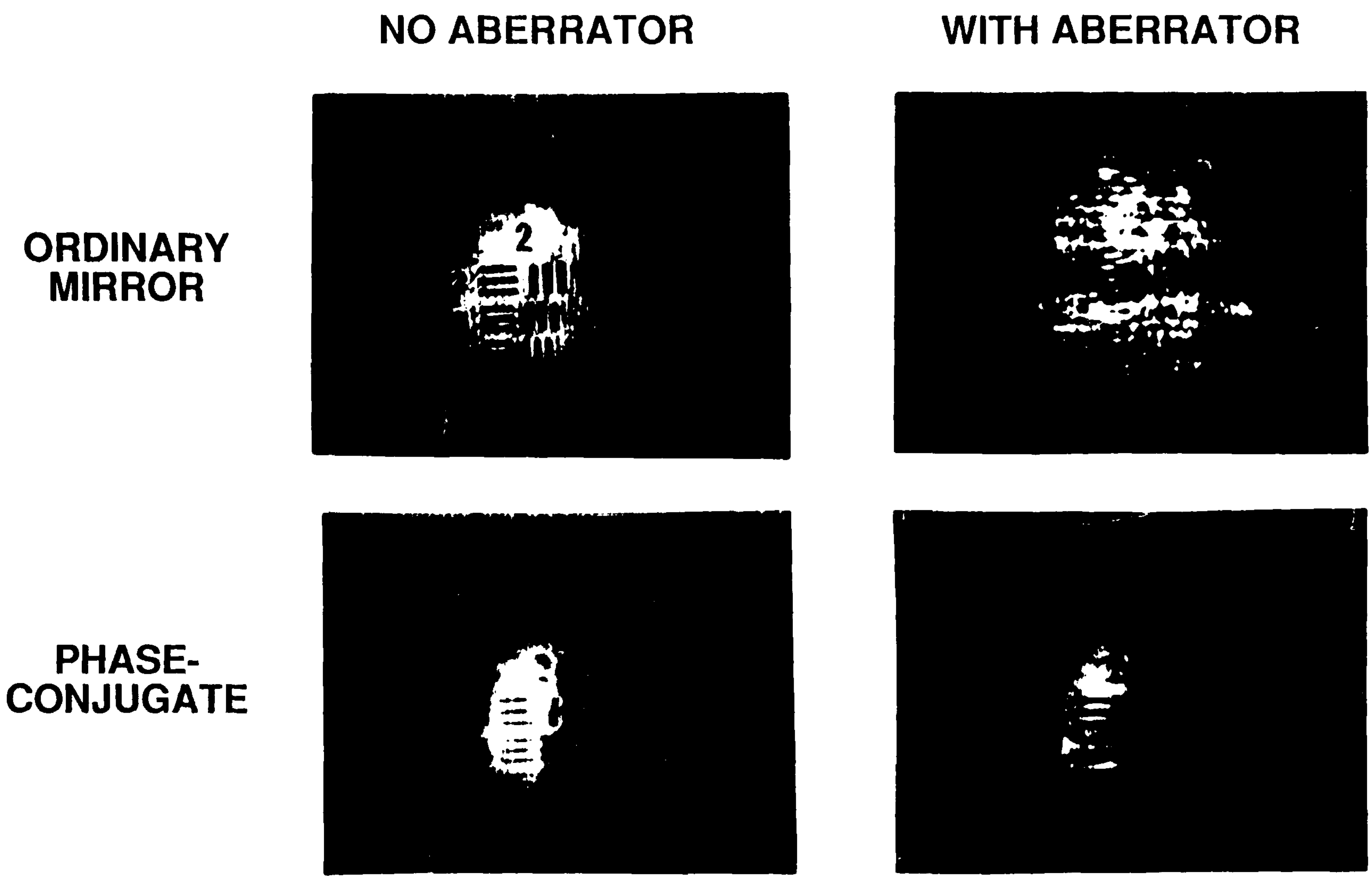

Figure 2. Aberration correction results obtained with 1 mm carbon disulfide cell.

distributed aberrators is a complex issue. As a minimum, however, the data indicates that this system could correct for a 2-cm thick aberrator centered about the ideal object plane if the total aberrator strength was equivalent to the etched glass plate.

The FWM interaction imposed limitations on the target-aberrator separation. If the target were imaged in the FWM, all spatial frequencies of the target would be in the interaction region and would be conjugated. As the image plane of the target is moved away from the FWM (by increasing the target-aberrator separation), higher spatial frequency components of the target spectrum will diffract out of the interaction region, and will not be conjugated. The effect can be seen in Fig. 2, where the image plane of the target was 20 cm from the FWM (or equivalently, the target-aberrator separation was 20 cm). Note the rounded edges of the phase-conjugate image, caused by higher spatial frequencies not being conjugated. In order to reduce this problem, the interaction region would have to be widened by using larger diameter pump beams. In this experiment, however, this was not practical because of the already low phase-conjugate reflectivity.

An alternative arrangement in which the pumps and the probe were colinear was attempted using the 10-mm cell. This approach would eliminate the mis-indexing problem while maintaining the strong phase-conjugate reflectivity associated with a longer interaction length. The approach also requires that the phase-conjugate be separable from the counterpropagating pump by polarization. (Thus, the half-wave plate in Fig. 1 would be absent in this scheme.) However, the very high degree of polarization discrimination required to separate the phase-conjugate from the counterpropagating pump could not be achieved. For example, if the phase-conjugate was three orders of magnitude less intense than the counterpropagating pump, a 1000:1 polarization discrimination ratio would be required just to provide a rather unsatisfactory 1:1 signal-to-noise ratio in the observed phase-conjugate beam. Therefore, the colinear scheme was not pursued. Instead, the cell length was reduced and the consequent decrease in phase-conjugate reflectivity was tolerated.

3.0 OPTICAL PARAMETRIC AMPLIFICATION

3.1 EXPERIMENT

The OPA portion of the combined experiment is shown in Fig. 3. The phase-conjugate from the one-way imaging portion of the experiment became the OPA signal and was combined with the OPA pump to propagate colinearly through the OPA crystal. The lithium iodate crystal, measuring 15 x 15 x 20 mm, was placed at the target image plane, where the camera had been during the one-way imaging experiments. After the crystal, the pump was separated from the amplified signal and idler by a color filter, and the amplified signal and idler were imaged onto the CID camera by a 20-cm lens.

The most demanding part of the OPA alignment was getting the pump and the signal to overlap and to be colinear through the crystal. Slight misalignments resulted in decreased amplification or circular fringes on the amplified image viewed with the camera. The fringes were caused by interference between the amplified signal and the idler. (This problem would not occur if these two beams were not of the same frequency and polarization.) By making the pump and signal propagate parallel to each other, the fringes could be centered, minimizing their adverse effects on the image. By then overlapping the parallel beams, the amplification could be maximized.

3.2. RESULTS

In order to avoid the possibility of crystal damage, the intensity of the OPA pump was filtered with an optical density of 0.75. Even at this pumping level, a signal amplification of about 100 was measured using summations of the pixel values from digitized images. Assuming an interaction length of 1.35 cm, based on a beam diameter of 1 mm and a walkoff angle of 4.2 deg, this amplification implies a pump intensity of about 340 MW/cm^2. By removing the density filters it would have been possible to obtain pump powers up to 1.9 GW/cm^2, which in turn would result

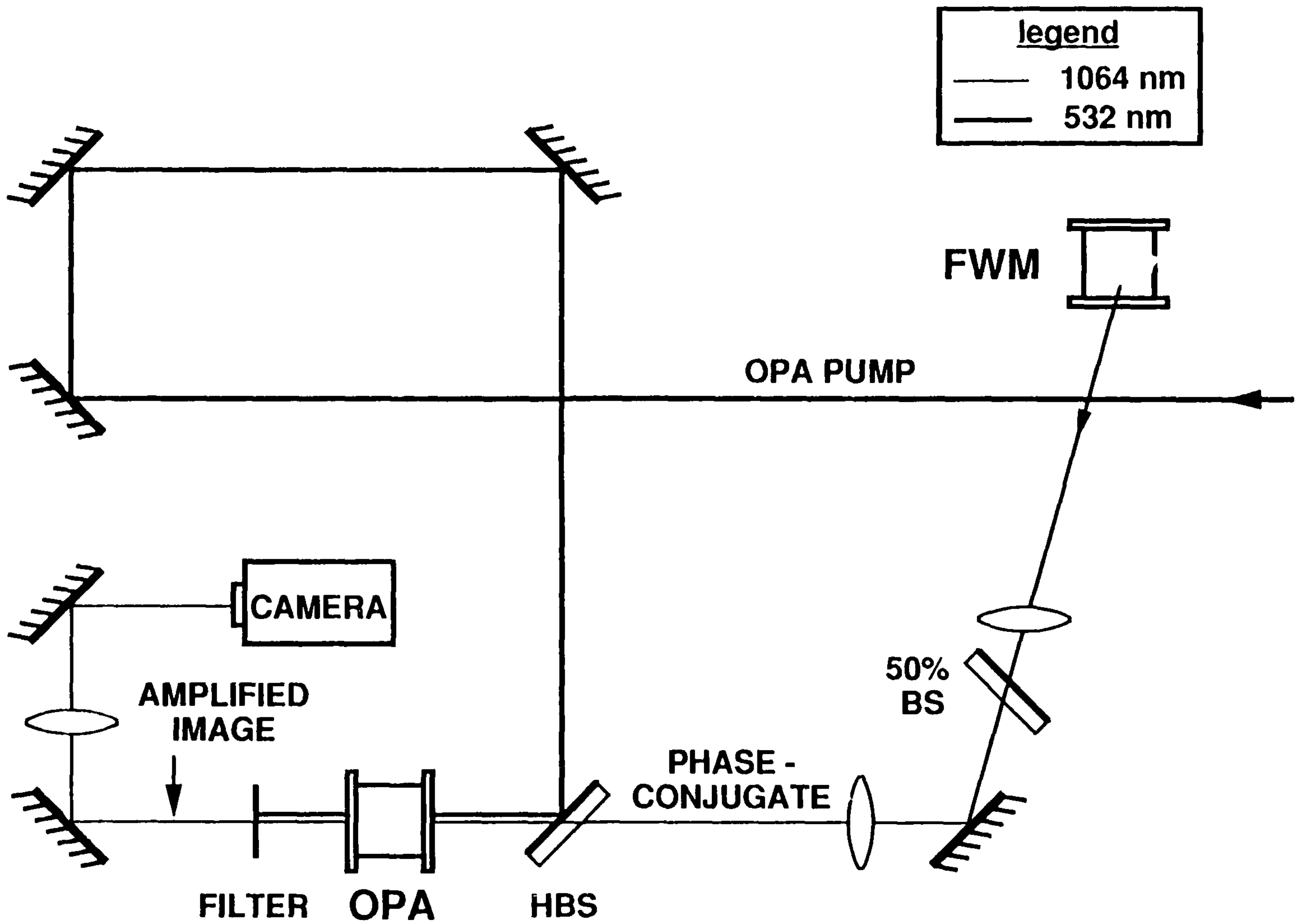

Figure 3. OPA Layout. BS: beamsplitter, HBS: harmonic beamsplitter.

in amplifications of up to 3.4×10^5, assuming that the amplification would not saturate at a lower value, because of pump depletion, and that the crystal would not be damaged. Thus, the potential amplification of this single-pass arrangement is high, and could be further increased by more pumping, or by choosing more favorable combinations of materials and wavelengths.

In addition to the amplification provided by the OPA, its effects on the image quality of the signal are also important. The spatial frequency selecting properties of the OPA in this experiment have already been established (Ref. 5). The initial plan was to exploit these properties in this demonstration by having the OPA discriminate between wanted and unwanted spatial frequency components of an image. Because of diffraction effects at the FWM, however, the higher spatial frequencies necessary to demonstrate this effect were not present on the phase-conjugate beam. Therefore, the OPA was used strictly as an amplifier in this case. The spatial frequency cutoff for this lithium iodate OPA, tuned to its phase-matching angle, was measured to be 9 lines per millimeter in Ref. 5 (measuring to the first null of the idler transfer function). This pass-band did not noticeably degrade the image as it was amplified.

As a side note, one previously unstudied aspect of the OPA theory was observed in this experiment. Section IV of Ref. 4 indicates that the amplified signal and the idler will, in general, image at different planes. For the degenerate downconversion case, Eq. 12 of Ref. 4 simplifies to $d_o = d_i$, where d_o is the distance in front of the crystal face ($z = 0$) at which the signal is imaged, and d_i is the distance after the crystal interaction length ($z = L$) at which the idler will be imaged. If $d_o = d_i = -L/2$, then the signal and idler will share a common image plane in the center of the crystal interaction length. This property was qualitatively observed in the laboratory. Initially, the phase-conjugate was imaged to the front face of the crystal ($z = d_o = 0$), and there was difficulty imaging the amplified signal clearly onto the camera with the 20-cm lens. This was because the idler had an image plane at $z = d_i = L$, where L was ≈ 1.3 cm. The lens

could not image the signal and the idler simultaneously. When the crystal was moved so that the phase-conjugate was imaged to the center of the crystal instead of the front face, the problem was solved, and the resulting signal and idler combination was much more clearly imaged on the camera.

4.0 CONCLUSIONS

Several important features of this system were discovered during this demonstration. First, the effects of a severe aberrator were corrected, but only when the nonlinear material was made thin enough (in this case 1 or 2 mm). Second, given the aberrator and imaging system tested, the aberrated pump and probe overlap requirements were very strict. This could be a difficulty in a system operating in a vibration-prone environment. Third, the OPA worked as predicted by previous work. Amplifications as high as one million should be attainable with an appropriately intense pump and a weak signal. Given a sharper image, the OPA could also selectively amplify portions of the image spectrum.

In summary, two nonlinear optical processes were integrated into a system capable of aberration correction and image amplification, although there were limitations. The target-aberrator separation was the limiting factor on the image resolution in this experiment, preventing exploitation of the OPA's spatial frequency selecting properties. In addition, the amount of amplification is limited only by the amount of pump intensity that the OPA crystal can withstand without damage.

REFERENCES

1. Ivakhnik, V. V., Petnikova, V. M., Solomatin, V. S., Kharchenko, M. A., and Shuvalov, V. V., "Single-pass systems for compensation of phase distortions," Soviet Journal of Quantum Electronics **10**, 514, 1980.

2. MacDonald, K. R., Tompkin, W. R., and Boyd, R. W., "Passive one-way aberration correction using four-wave mixing," Optics Letters **13**, 485, 1988.

3. Alley, T. G., Kramer, M. A., Martinez, D. R., and Schelonka, L. P., "Single-pass imaging through a thick, dynamic distorter using four-wave mixing," to be published in Optics Letters, 1 Jan 1990.

4. Gavrielides, A., Peterson, P., and Cardimona, D. "Diffractive imaging in three-wave interactions," Journal of Applied Physics **62**, 2640, 1987.

5. Laferriere, P. A., Wetterer, C. J., Schelonka, L. P., and Kramer, M. A., "Spatial frequency selection using downconversion optical parametric amplification," Journal of Applied Physics **65**, 3347, 1989.